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Study of Stably Stratified Flows and Ventilation over Idealized Street Canyons using a Single-Layer Hydraulics Model

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Outline

- Background
- Objectives
- Methodology
- Results
- Conclusions

Stability of Atmospheric Boundary Layer

Table 1. Properties of the shallow-water one-layer model in the US standard atmosphere.			
	Thickness of fluid layer H (m)		
	200	500	1,000
Air density ρ (kg m^{-3})	1.202	1.167	1.112
Air temperature θ (K)	286.85	284.9	281.650
Brunt-Väisälä frequency N (sec^{-1})	0.0306	0.0304	0.0301
Froude number Fr	**1.635**	0.658	0.332
Remark: It is assumed that the gravitational acceleration g = 9.81 m sec^{-1}, the fluid velocity U = 10 m sec^{-1}, ambient fluid density ρ_0 = 1.225 kg m^{-3} and θ_0 = 288.15 K.			

Buoyancy Frequency

$$N^2 = -\frac{g}{\rho}\frac{d\rho}{dz}$$

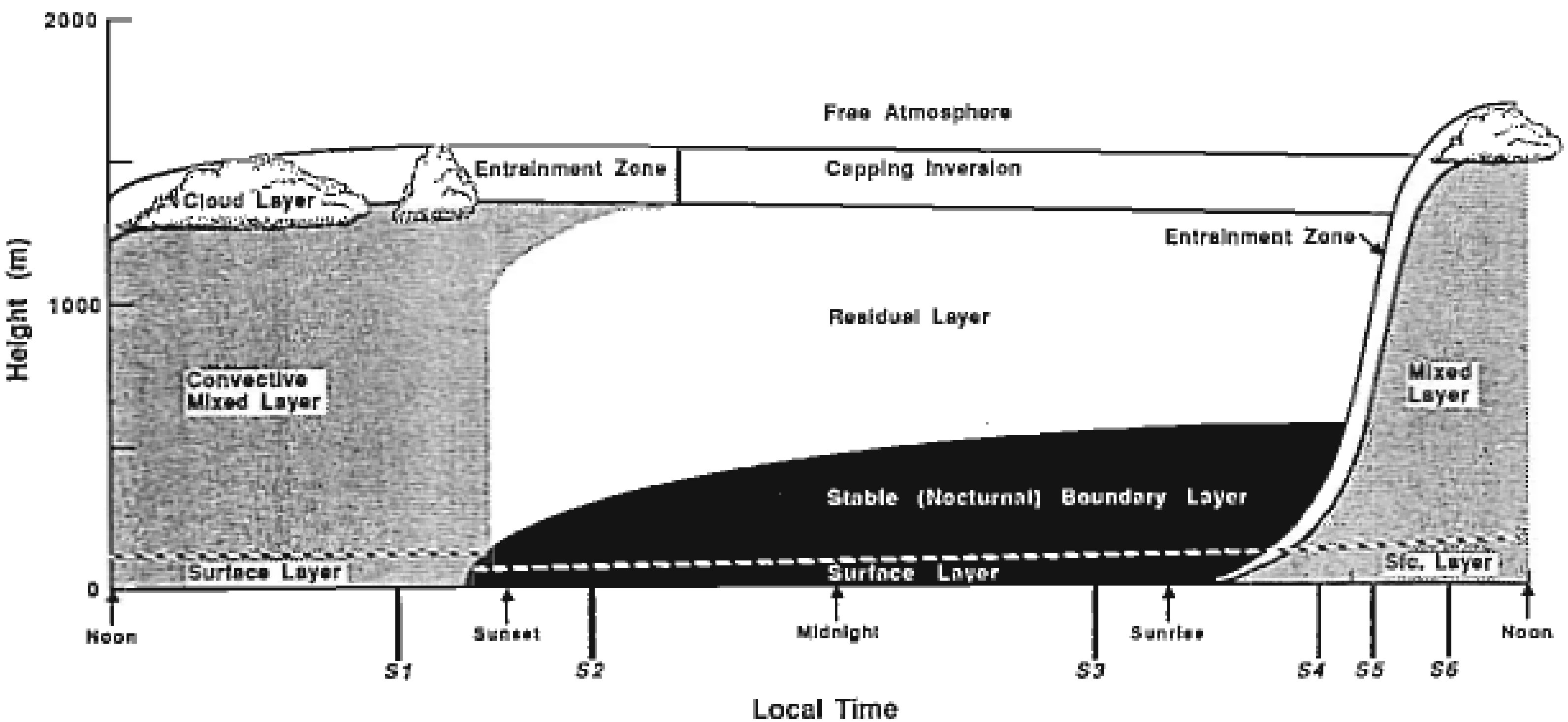
Froude number

$$Fr = \frac{U}{ND}$$

- Normally known as density stratified flow – density of the fluid varies with vertical position
- Commonly occur in atmosphere and ocean – can be continuous or discontinuous
- The buoyancy force acting on the density stratified flow has dominant effect if sufficient time is given
- Characterize with Buoyancy Frequency *N* and Froude Number *Fr*

Stably Stratified Boundary Layer

- Atmospheric boundary layers can be classified into 3 different types namely:
  - Neutral boundary layer – Buoyancy effect are negligible
  - Convective boundary layer – Positive Buoyancy effect, e.g. Day time
  - Stable boundary layer (SBL) – Negative Buoyancy effect, e.g. Night time



Stull, 1988

Stably Stratified Boundary Layer

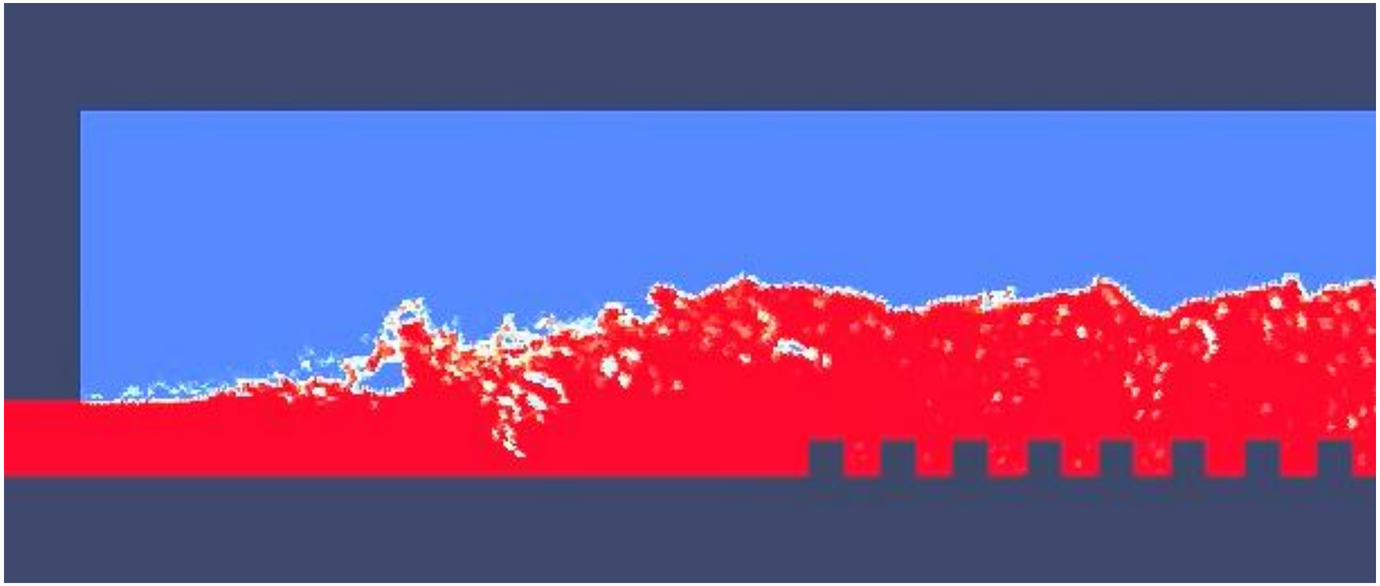
- SBL can also be formed by warmer airflow over colder surface, e.g.
  - Warmer air from land flowing over colder water near coastal areas
  - Radiative cooling of the ground surface

- It is important to study SBL because:
  - The boundary layer depth of SBL is much shallower; therefore, concentration of pollutants increases
  - The negative buoyancy destroys eddies generation and therefore weakens mixing and air ventilation performance
  - The trapped pollutants may boost chemical reactions which might become harmful to inhabitants

- Although studies of weakly SBL is well established in various text books and literatures, most fundamental features of strongly SBL remains unknown

Atmospheric Hydraulic Jump in SBL

- In general, negative buoyancy in SBL suppresses eddies generation, thus negatively affects ventilation performance
- However, hydraulic jump, which occurs in SBL, dissipates excessive kinetic energy into turbulence may enhance both upstream and downstream vertical mixing as well as its ventilation effectiveness
- Hydraulic jump is a sudden transition from critical flow (*Fr* > *1*) condition to subcritical flow (*Fr* < *1*) condition



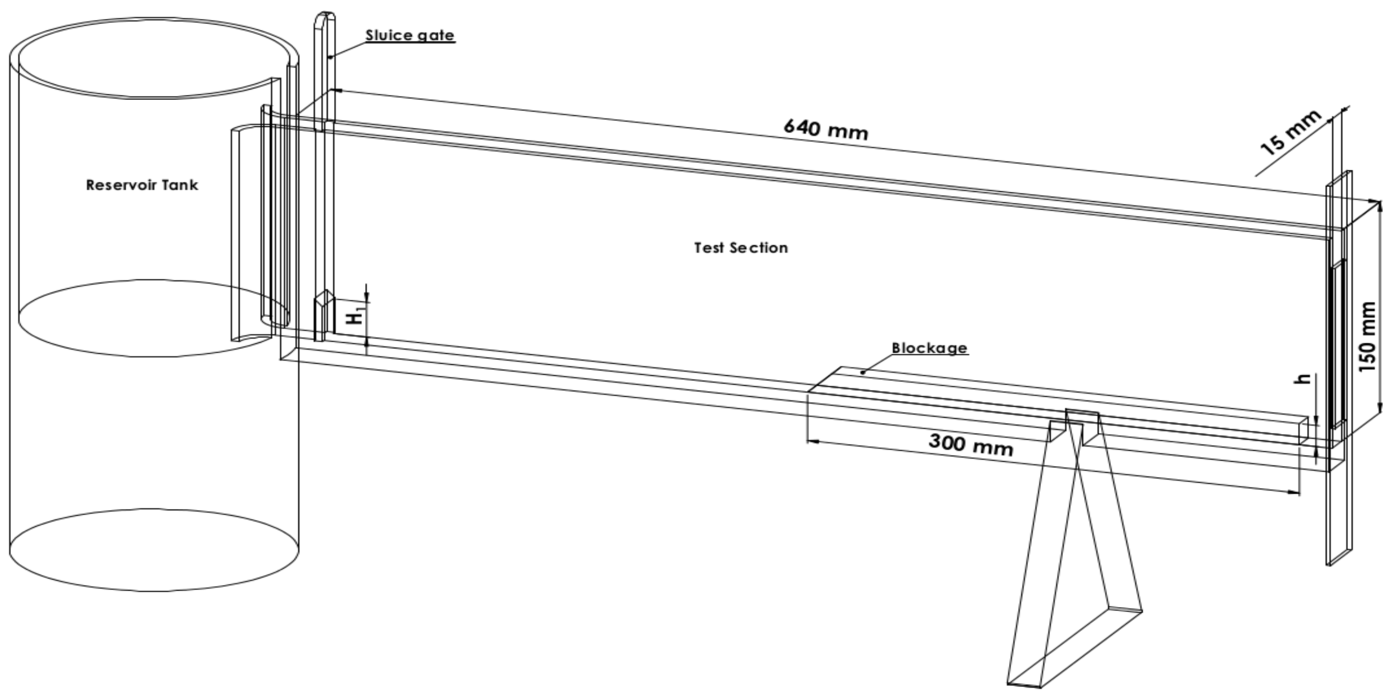
Objectives

- Study of ventilation and mixing performance of idealized street canyons under SBL conditions
- Examine the features of high Froude Number flows with simplified SBL conditions by single-layer model
- Determine whether environmental hydraulic jump promotes ventilation performance in urban areas
- ~~Investigate the opportunities for urban planning under SBL conditions~~

Miniature Water Channel

- The miniature water channel can easily provide adequate upstream flow velocity (approx. 1.1 m sec^{-1}) to produce enough Fr for the hydraulic jump
- Fr is adjusted by the opening (H_1) of sluice gate and volumetric flow rate (Q)
- Hydraulic jump is induced by the abrupt blockage with height (h)

$$Fr = \frac{U}{\sqrt{gH_1}}$$



CFD Model - LES

- Code – OpenFOAM 2.1.1
- Large-eddy Simulation (LES) with volume if fluid (VOF) multiphase model

Continuity

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0$$

Momentum

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\bar{u}_i \bar{u}_j = -\frac{\Delta P}{\Delta x}\delta_{ij} - \frac{\partial \bar{\pi}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} + g'$$

VOF model, β denoted the fraction of the fluid phase

$$\frac{\partial \beta}{\partial t} + \bar{u}_i \frac{\partial \beta}{\partial x_i} = 0$$

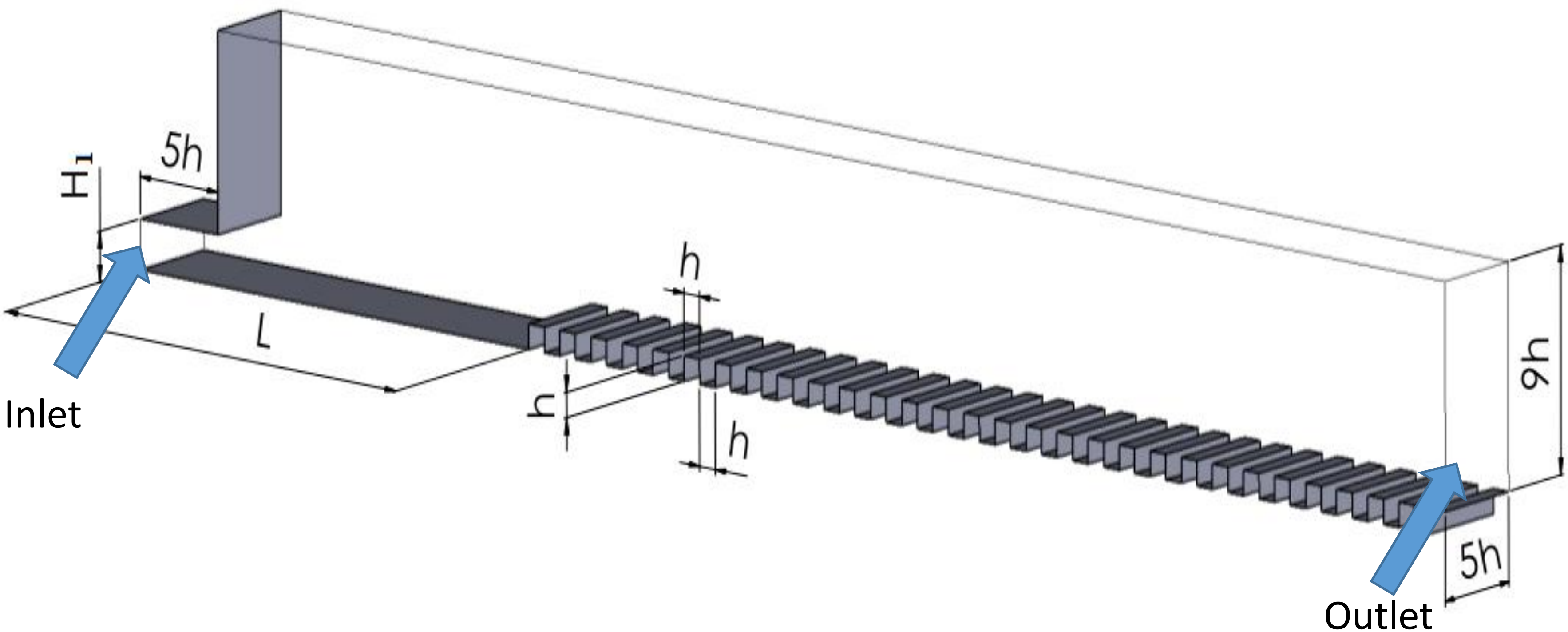
Computational Domains

Computational Model

- 30 Street canyons
- No. Cells ≈ 7 million “prism”
- $y^+ \approx 10$
- Reynolds number ≈ 10,000

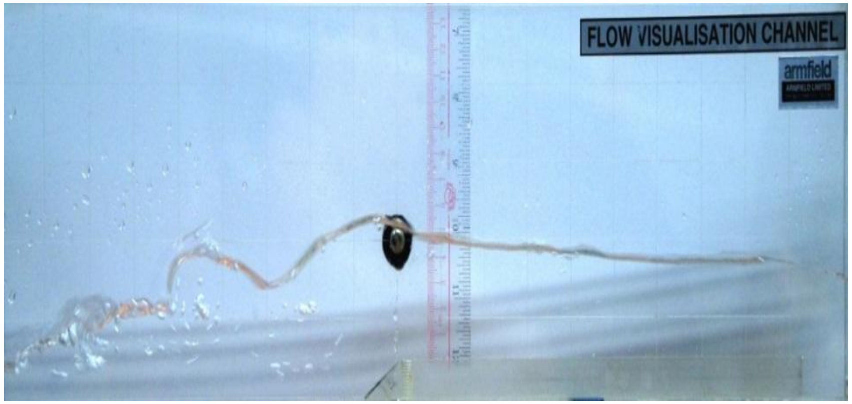
Boundary Conditions

- Grey areas are non-slip walls
- Front and Back are cyclic
- Inlet is bulk velocity inlet
- Top and outlet with total pressure = 0



Observations from Miniature Water Channel

- The quasi-equilibrium state of hydraulic jump will take some time to establish
- Location of the toe of the jump depends on upstream Froude number (Fr_u)
- There exist a critical Froude number (Fr_c) that the hydraulic jump will transit from a standing hydraulic jump to high Fr jump

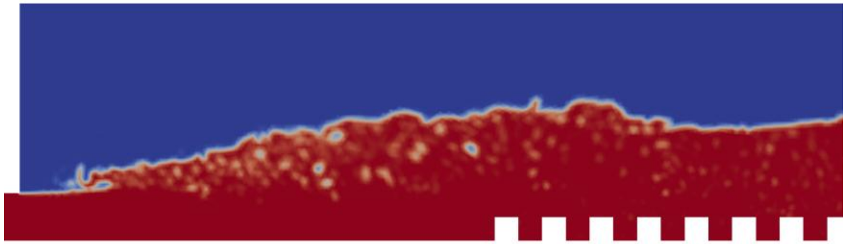


$Fr_u < Fr_c$

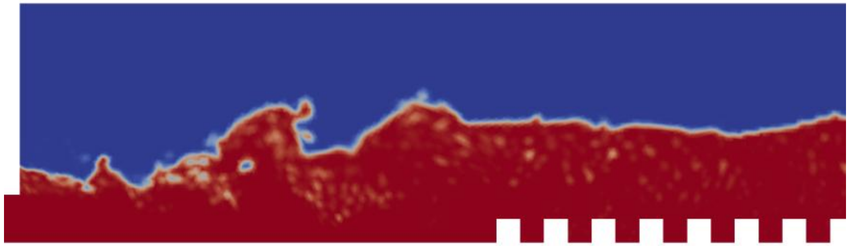
$Fr_u > Fr_c$

LESs

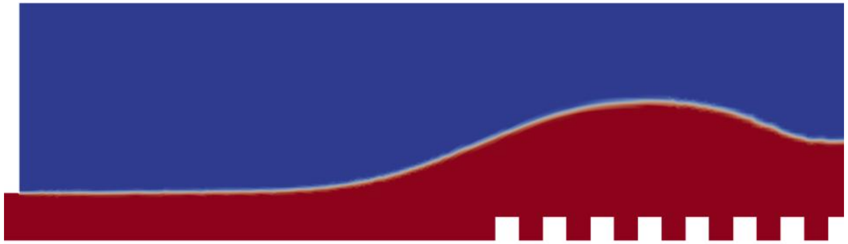
- The critical Fr_c was found to be around 2.4 for computational domain with $\frac{h}{H_1} = 0.5$
- For $Fr < Fr_c$, the toe of the jump will move towards the upstream side
- For $Fr > Fr_c$, the jump transit into high Froude number jump



$Fr = 2.4$



$Fr = 2.2$



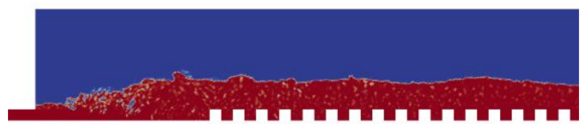
$Fr = 2.6$

LES Simulations

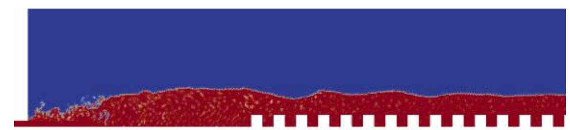
- Hydraulic jumps were successfully simulated with the followin settings

h/H_1	0.25	0.5	0.8	1	1.6	2.0
Fr	1.7	2.4	2.8	3.1	4.0	4.6

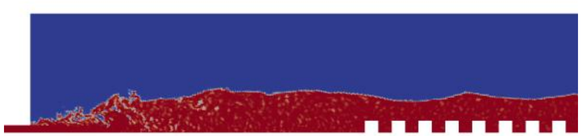
$Fr = 1.7$



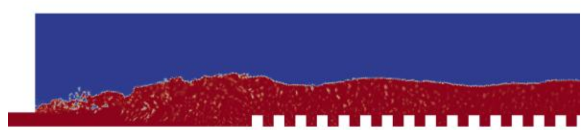
$Fr = 2.4$



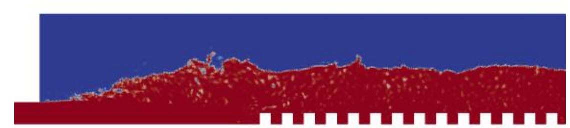
$Fr = 2.8$



$Fr = 3.1$



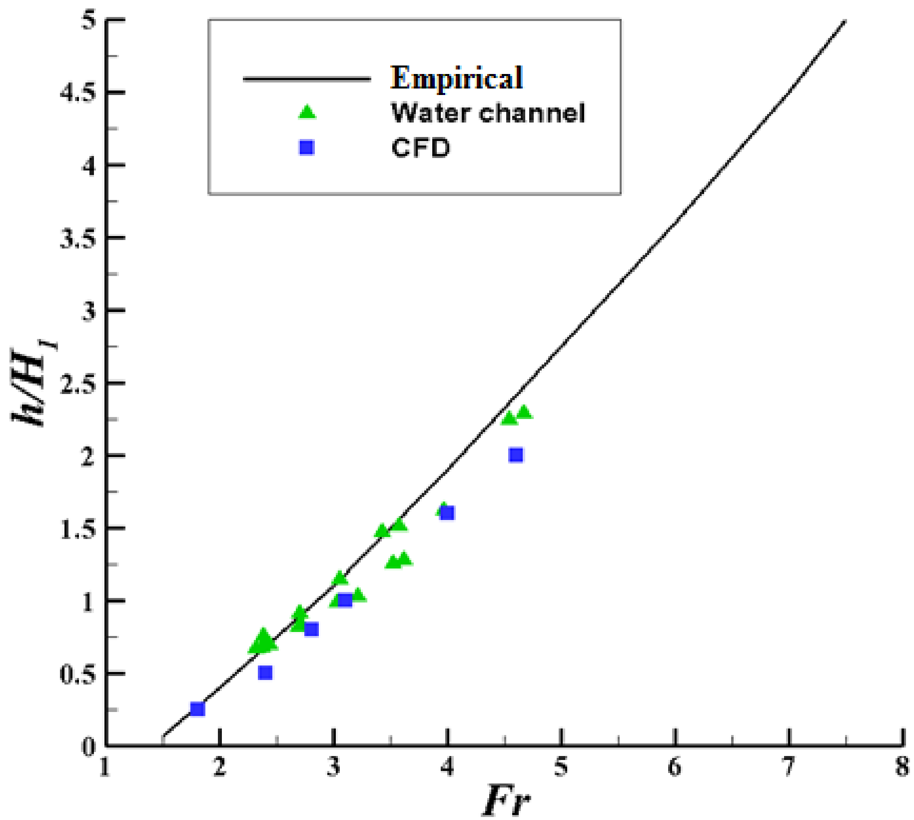
$Fr = 4.0$



$Fr = 4.6$

Verification and Validation

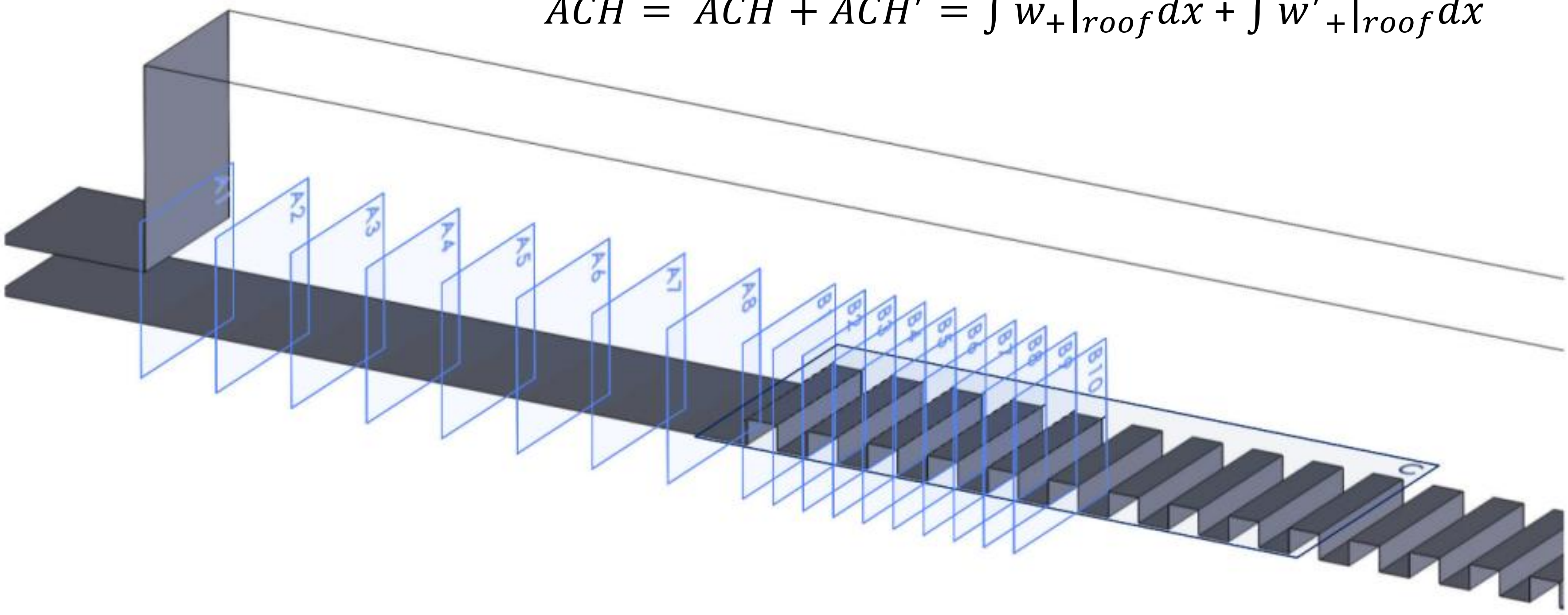
- Both the water channel and CFD results were compared with the empirical formula (Forster, 1949)



Velocity profiles and Ventilation performance

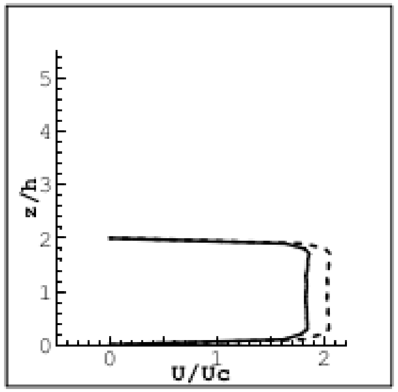
- The fluid flow velocity profiles of CFD model with $\frac{h}{H_1} = 0.5$ were examined
- Profiles were separated into Section A (Upstream) and Section B (Downstream)
- The ventilation performance is measured aloft the street canyons with a parameter ACH (Liu etal, 2015)

$$ACH = \overline{ACH} + ACH' = \int \overline{w}_{+}|_{roof}dx + \int w'_{+}|_{roof}dx$$

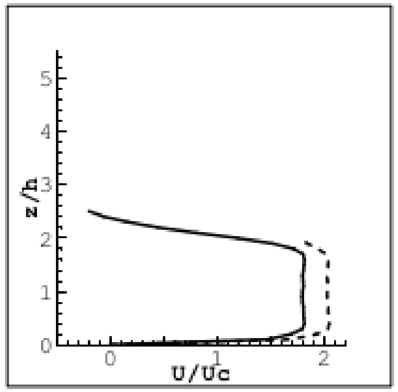


Flow profile – Upstream (Section A)

- Velocity is normalized by the critical velocity (U_c) which corresponding to $Fr = 1$



A1



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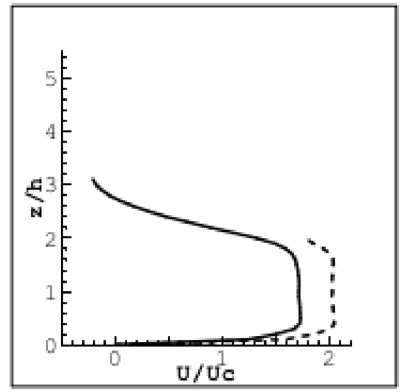
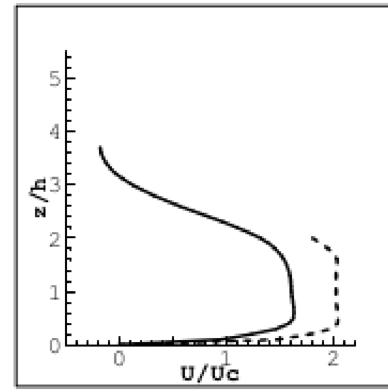


A3



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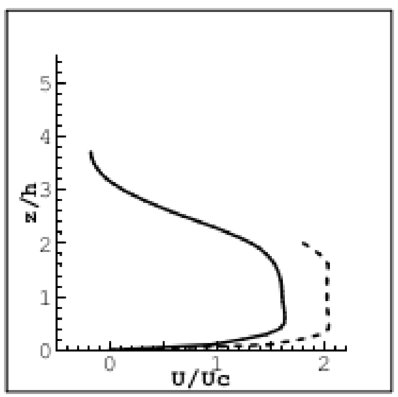

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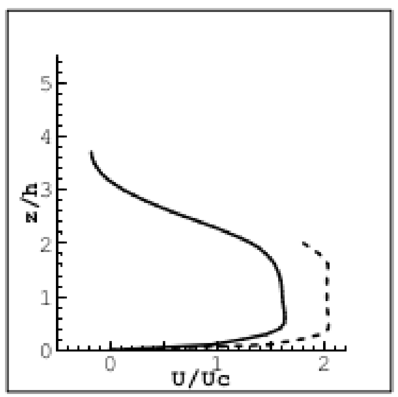

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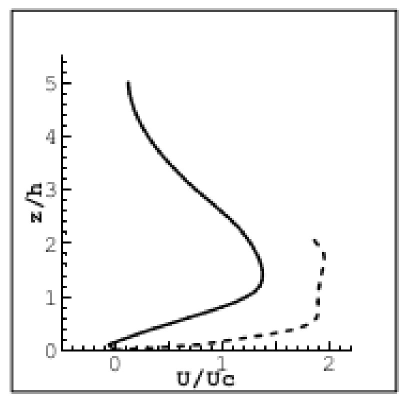

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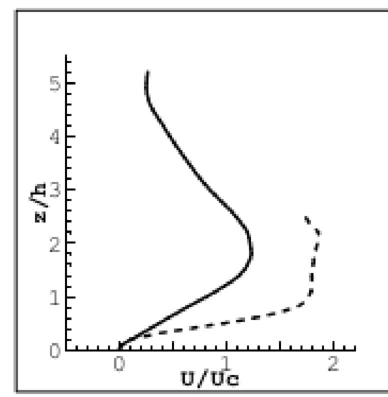
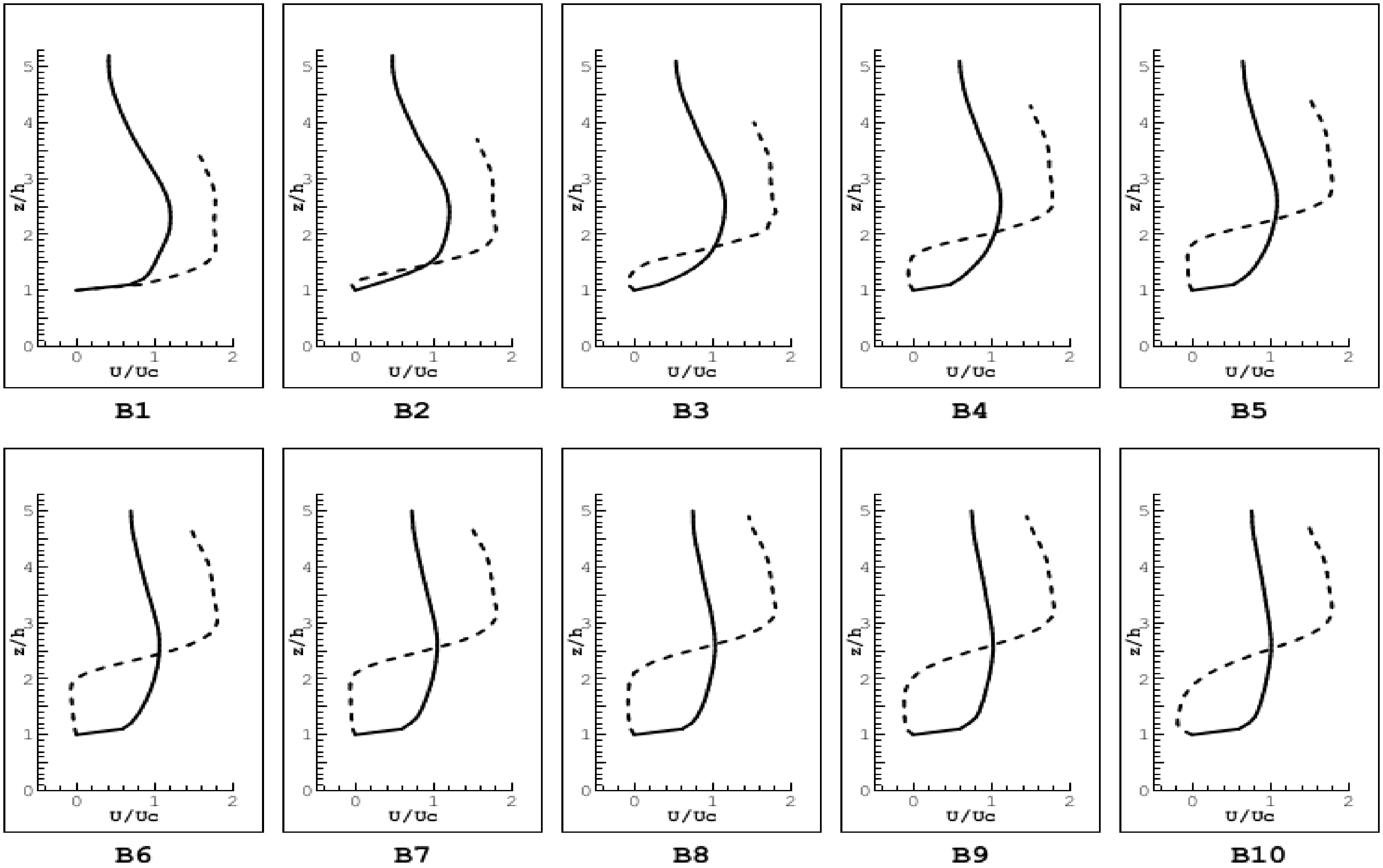


A8

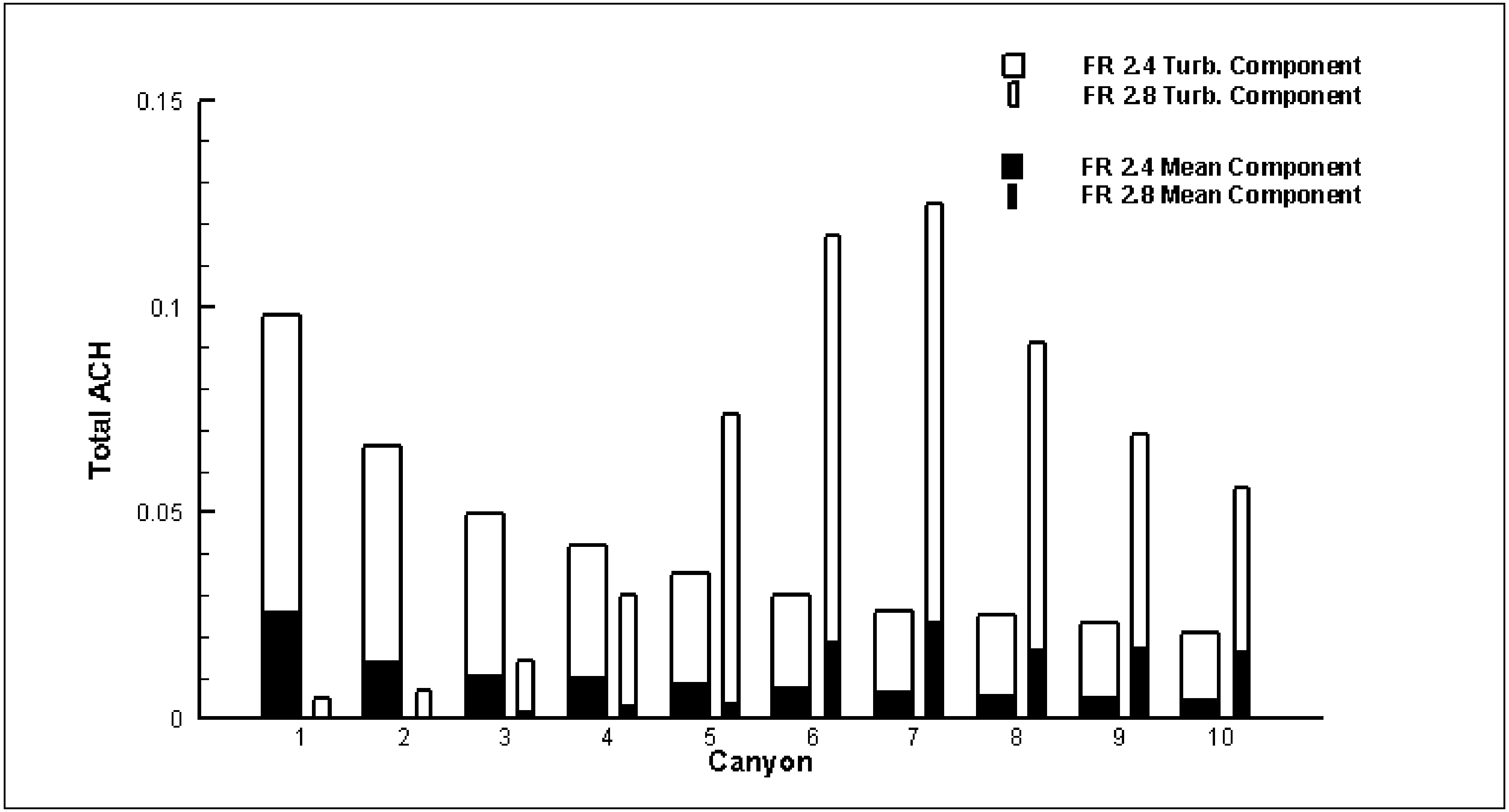
Flow profile – Downstream (Section B)



Results

Ventilation performance over street canyons (Section C)

- Compared the two different ventilation mechanism
  $Fr = 2.4\ (hydraulic\ jump)\ and\ Fr = 2.8\ (high\ Froude\ number\ jump)$



Conclusions

- The single layer hydraulic model tends to over simplify the interactions happening in SBL; however, it provides some useful information and easy analysis with traditional theories
- Different in Froude number substantially modify the ventilation mechanism over the idealized street canyons under SBL, ~~which may indicate that there is an opportunity for urban planning improvement~~
- The CFD results indicate that the boundary height and building height have major effects on the flow mechanism

Thank you!

Q&A

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